

ATTACHMENT 3

**GROUNDWATER FLOW AND SOLUTE TRANSPORT MODEL
FOR TOOEELE ARMY DEPOT**

Groundwater Flow and Solute Transport Model for Tooele Army Depot, Tooele, Utah

1. Background

A. From 1968 to 1988, various hazardous wastes produced by TEAD activities were disposed in wastewater which flowed through four unlined ditches to an unlined Industrial Waste Lagoon (IWL). These disposal practices led to groundwater contamination which the U.S. Army Corps of Engineers (USACE) began investigation in 1979. The IWL was closed in 1988. A RCRA post-closure permit was subsequently issued for the site on January 7, 1991. After several assessments and investigations, a pump and treat system to isolate and remediate TCE contamination in the groundwater was designed and constructed. The system was placed in operation in the fall of 1993. The groundwater treatment system consists of 16 extraction wells and 13 injection wells, along with two stripping towers designed to treat up to 8,000 gpm.

2. Purpose of Modeling Efforts

A. From January 1993 to the present, the U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC) has developed a series of computer models for simulating groundwater flow conditions at the Tooele Army Depot (as specified in Volume I, Table V-3). This included:

- (1) The initial flow model (1994)
- (2) A transient application/analysis using the initial model (1995)
- (3) An analysis of boundary effects and the influence of bedrock anisotropy on flow paths (1997).
- (4) A post-pumping steady-state calibration (1997)

B. The primary objective of these modeling efforts shall be to provide a tool for determining optimum pumping rates and locations, which shall ensure the hydrodynamic isolation of the TCE plume below and to the north of the closed Industrial Waste Lagoon (IWL).

3. Abstract of Modeling Efforts

A. 1998 Flow and Transport Model (HEC, 1998)

(1) In 1994, a three dimensional finite difference flow model was used to simulate groundwater flow at a TCE contaminated site within the Tooele Army Depot. The modeled area of 15,600 feet by 24,000 feet was overlain by a 51 x 80 grid of square cells 300 ft on each side. The model was constructed in 3 layers simulating confined and unconfined flow conditions. Relative to the 1994 model, in the 1998 model represents an extension of 4,200 ft to the northeast, 3,000 ft to the northwest, and 6,000 ft to the southeast. The model was extended to

the northeast to reduce model boundary effects. The model was extended to the northwest to allow for the simulation of the natural attenuation of groundwater contaminants. The model was extended to the southeast to incorporate key data points in the Industrial Area. The 1998 model covers a total of 19,800 feet by 33,000 feet. The model area was overlain by a grid of 99 columns and 165 rows of square cells, 200 ft on each side. The total number of model cells increased from 12,480 cells in the 1994 model, to 49,005 cells in the 1998 model. The flow model utilized head-dependent flux, recharge, and specified flow boundaries to represent the hydrogeologic setting.

(2) Two model calibrations were performed; a pre-pumping calibration to water levels which were averaged over 4 seasonal measurements taken between June of 1992, and September of 1993; and a calibration to water levels which were measured in March of 1997., approximately 3 years following the commencement of operation of the pump-and-treat system. A total of 58 water elevations were selected as calibration targets for the pre-pumping calibration study, and a total of 61 water level measurements were used as calibration targets for the post-pumping calibration study. Values of hydrogeologic parameters were derived from field measurements and past regional studies. Transmissivity values from model calibration showed good correlation to transmissivity values estimated from aquifer tests, bedrock pressure tests, and regional flow estimates.

(3) The particle tracking model MODPATH was applied to both pre-pumping and post-pumping scenarios. Results from particle tracking analysis illustrated the controlling influence the uplifted bedrock block has on groundwater flow paths. An initial contaminant transport model was developed using the code MT3D. Results from the transport model indicate that significant reduction in total pumping rates can be incurred by optimizing the extraction system to focus on contaminant concentrations exceeding 50 ppb. Additionally, by adjusting clean-up levels to 50 ppb, model results indicated that minimal environmental impact from the migration of the lower concentration plume downgradient due to natural attenuation. Future investigations will concentrate on identifying contaminant sources and delineation the northeast boundary of the uplifted bedrock block.

B. 1999 Flow and Transport Model (HEC, 2000)

(1) The primary purpose of this calibration effort was to construct an additional model layer to better delineate the location of the bedrock block in the alluvium to the southeast of the uplifted bedrock block.

(2) Previous models of the site consisted of an upper layer (layer 1) located from the water table to a depth of 150 ft. Layer 2 was specified to have a thickness of 150 ft and was located beneath layer 1. Layer 3 was specified to have a thickness of 300 ft and was located beneath layer 3. Thus, past models simulated this area as having a thickness of 150 ft of alluvium overlying the bedrock. Since the construction of the original 1994 model, additional field evidence has indicated that the southern alluvium was significantly thinner than 150 ft. The purpose of this study was to better simulate this zone.

(3) Additionally, this study incorporated the most recent field data available. Water level data as recent as October 1999 was used in "post-pumping" calibration runs. Average extraction and injection rates were derived from the total volume of pumping from the commencement of the system operation to October 1999.

C. 2000 Flow Model (HEC, 2000a)

(1) The 2000 model consists of 4 layers, 165 rows, and 99 columns. Model cells are 200 ft square. Model layer thickness is specified relative to water table elevation. Layer 1 is 50 ft thick layer 2 is 100 ft thick, layer 3 is 150 ft thick, and layer 4 is 400 ft thick.

(2) As the uplifted bedrock is a controlling hydrogeologic feature at the Tooele study site, the slightest conceptual alternation of the location or permeability of the bedrock block results in significant changes in flow and water levels throughout the study area. In 2000, a geophysical survey was conducted along the northeast boundary of the Tooele Army Depot. This resulted in a new conceptualization of the bedrock location. The primary purpose of the 2000 calibration effort was to incorporate this new information on the location of the bedrock block.

(3) The work performed for this recalibration included the following:

(a) Reconceptualization of the northeast bedrock block based on interpretation of geophysical data.

(b) Incorporation of the conceptual location southeast bedrock block according to boring log interpretations.

(c) The zone of low hydraulic conductivity (K) fault gouge encasing the uplifted bedrock block in the central area of the site was reconstructed.

(d) A new zone of a slightly higher K was incorporated in layer 1, northeast and up gradient of the bedrock block. This allows for more flow into the bedrock block in the northeast area as indicated by increasing contaminant levels in the area.

(e) The addition of a head dependant flux boundary condition along the northeast model boundary. This allows water to flow off-site to the northeast.

(f) The southwestern displaced sediments zone was realigned to trend in a more geologically realistic direction

(g) The northeastern displaced sediments zone was realigned to trend in a more geologically realistic direction.

D. 2001/2002 Recalibration Study (HEC 2001/2002)

(1) The 2001/2002 ground water flow model consisted of a reconstructed 9 layer model, consisting of 165 rows and 99 columns with 200 ft square model cells.

(2) The 9 layer structure of the model resulted in a more precise delineation of the hydrologic system. Additionally, the new layer structure included thinner layers in the upper 300 feet of the model domain, allowing for a more accurate simulation of contaminant transport in the future.

(3) A revised conceptual model of the study area was integrated into the model. This resulted in the adjustment of the bedrock location, the relocation of the southwestern displaced sediments zone, and the creation of two new fault zones.

(4) The model was calibrated to two sets of water level data: 157 water levels representing Spring of 2001 conditions, and the average of 7 semi-annual measurements at 54 wells between Spring 1997 to Spring 2001. Model conceptualization was initially based on the larger Spring 2001 data set. The model was then calibrated to the averaged data set. A final calibration was performed with the goal of achieving the best fit between the two data sets. By attaining a good calibration with both data sets, the 2001/2002 modeling study provided validation for the use of the new, larger data set in future calibration studies.

(5) The following tasks were completed as part of the 2001/2002 modeling study:

(a) The model was reconstructed as 9 layers. Layer bottom elevation were specified as constant through the entire model domain. Layer thickness in the southern alluvium was reduced to 25 feet in the upper two model layers. Layer thickness in the northern alluvium was reduced to 25 feet in the upper layer.

(b) Data quality analysis was performed on Spring 2001 and Fall 2001 water level measurements. Significant discrepancies between the two data sets were discovered. This was the result of varying extraction well rates in the bedrock area. Thus, it was determined that the Fall 2001 data should not be used in this calibration study.

(c) Data quality analysis was performed on 174 Spring 2001 water level measurements. This resulted in the removal of 17 water level measurements from the calibration study.

(d) Extraction and injection pumping well data through Spring 2001 was incorporated into the model.

(e) the coordinates of observation wells used in the calibration study were adjusted to the most recent survey data.

(f) The screened elevations of pumping wells and observation wells were incorporated into the model.

(g) The location of the uplifted bedrock block was reconceptualized based on potentiometric and geophysical data interpretations.

(h) The location of the southwestern displaced sediments zone was reconceptualized based on Spring 2001 water level data.

(i) Water level measurements from the recently constructed D-wells at the eastern end of the study area were integrated into the calibration process. A low permeability fault zone was created to allow for the simulation of a sharp drop in water levels measured in the proximity of the D-wells.

(j) Specified heads of boundary conditions at the southeast, northeast and northwest model boundaries were adjusted to reflect ground water table elevations according to revised ground water contour maps.

(k) The model was calibrated to two sets of water level data: 157 water levels representing Spring 2001 conditions and the average of 7 semi-annual measurements taken at 54 wells between Spring 1997 to Spring 2001.

E. 2003 Groundwater Flow and Transport Model (HEC, 2003)

(1) This model calibration study included several changes and additions to the prior models. Changes and additions consisted of:

(a) The model grid was extended 2,000 feet to the northeast to allow for a more accurate representation of flow at the northeast boundary.

(b) An algorithm was developed for the simulation of more representative well extraction rates.

(c) A revised conceptualization of bedrock, based upon geophysical studies, was integrated into the model.

(d) A much larger calibration data set was incorporated allowing for a more complex and accurate numerical representation of the site.

(e) The analysis also included the calibration of the transport model.

(2).. The model was calibrated to 184 water levels measured in the spring and fall of 2002. Additionally the model was calibrated to regional estimates of subsurface inflow, measured drawdown in the uplifted bedrock block and the migration of the TCE plume.

(3) The final model head calibration produced an absolute mean error of 1.76 ft. The absolute mean error of the prior (2001/2002) calibration study was 1.94 ft. The prior study used 157 calibration targets. The final model also reproduces the approximately 40 ft observed

drawdown in the bedrock block due to groundwater pumping, and it matches prior estimates of groundwater inflow along the southeast boundary.

(4) The TCE plume produced by the model is a reasonable match to the observed plume, with a few noted exceptions.

(a) The model under predicts some concentration in the northern alluvium, but may over predict concentrations in other areas of the model.

(b) The simulated northeast plume is significantly different from the measured northeast plume.

(c) Approximately 992 kg of TCE have been removed by the groundwater extraction and treatment system. The model simulates a high TCE removal of 1430 kg. These facts suggest that either the modeled mass from source areas is too high or that the treatment system is less effective than modeled (or both). However, reduction in the source strength would lead to a poorer match to observed TCE concentrations, and reductions in extraction rates would not be realistic.

F. 2004 Groundwater Flow and Transport Model (HEC/Geotrans, 2004)

(1) This model calibration study includes several changes and additions to the prior models of TEAD. Changes consisted of:

(a) The model grid was extended 10,200 ft to the northeast and 1,200 ft to the southeast to allow for a more accurate representation of the regional flow regime.

(b) A revised conceptualization of the bedrock, based upon recent geophysical studies and analysis of bore logs, was integrated into the model.

(c) Three new Tooele City production wells were input into the model. The incorporation of a larger calibration data set allowed for a more complex and accurate numerical representation of the site.

(d) A transport model calibration was also included in this analysis.

(2) The model was calibrated to 195 water levels. Additionally the model was calibrated to regional estimates of subsurface inflow, measured drawdown in the uplifted bedrock block, and the migration of the TCE plume.

(3) The TCE plume produced by the model is a reasonable match to the observed plume, both under current conditions and development of the plume. The modeled results compare better with observed results than the prior model (HEC, 2003) particularly for the northeastern boundary plume area. There are a few noted exceptions where the model does not match observed conditions as well as other areas. In particular, the model under predicts some

concentrations in the northern alluvium, but may over predict concentration in other areas of the model.

(4) Approximately 992 kg of TCE have been removed by the groundwater extraction and treatment system since June 2002. The model simulates removal of 1135 kg, which is within ten percent of measured.

G. Addendum, 2004 Groundwater Flow & Transport Model (HEC/Geotrans, 2004a)

(1) Due to time constraints for submittal of the 2004 model, the planned transport sensitivity analysis for 2004 was not completed in time for inclusion in the document. This addendum documented the TCE transport sensitivity analysis conducted subsequent to the model submittal.

(2) Prior to conducting the TCE transport sensitivity analysis, a sensitivity analysis on the groundwater flow model was performed by varying hydraulic conductivity of specific structural features of the site, hydraulic conductivity of subsurface material of the entire site, and areal recharge.

(3) The sensitivity analysis for the TCE transport model involved changes to parameters that directly affect TCE movement, but do not alter the groundwater flow field. These parameters were:

- (a) Effective porosity
- (b) Distribution coefficient (K_d)
- (c) Dispersivity
- (d) Source area loading

(4) In addition to the above parameters, the model was run with two additional numerical techniques for solving the solute transport equation.

(5) The sensitivity analysis conducted will be used to guide the scope of the 2005 model calibration and uncertainty analysis. Recommendations are provided in this document for future analysis.

H. 2005 Groundwater Flow and Transport Model (HEC/Geotrans, 2005)

(1) Recovery data following the summer 2004 shutdown of the groundwater treatment system facilitated a more accurate delineation of the bedrock encasing zone and faults, providing a significantly more accurate representation of the flow system. This resulted in an improved conceptualization of a controlling hydrologic feature of the site. The encased bedrock zone was expanded to the south and northwest relative to the 2004 model.

(2) The flow model was calibrated to four data sets consisting of:

- (a) Water levels measured in June 2004;

- (b) Water levels measured in September 2004;
- (c) A long-term average data set; and
- (d) Transient data from recovery following shutdown

(3) The model generally reproduces recovery curves in the bedrock block and alluvium due to shutdown of groundwater pumping. The model also matched prior estimates of groundwater inflow into the model domain, and simulated the general regional flow domain.

(4) The TCE plume produced by the model is a reasonable match to the observed plume, both under current conditions and during the development of the plume. The model results compare favorably with observed results and the prior model (HEC/Geotrans, 2004).

(5) Calibration to the recovery data and subsequent sensitivity analyses were used to analyze the relative influence of parameters on transient water levels. Changes in horizontal hydraulic conductivity primarily affected the total simulated head change over a time interval. Changes in vertical hydraulic conductivity and specific storage primarily affected the initial rebound following shutdown. Changes in specific yield/porosity primarily affected the slope of the recovery curve.

(6) The steady-state and transient calibrations demonstrated the model's ability to replicate changes in water levels resulting from changes in stress on the system. The good match with several independent data sets provides additional validation and reduces the uncertainty of the model. Porosity is important for simulating plume migration. In the past porosity was estimated from tables. Calibration to measured recovery provided a physical basis for porosity values in bedrock and alluvium.

I. 2006 Groundwater Flow and Transport Model (HEC/Geotrans, 2006)

(1) Groundwater level recovery data following the summer 2004 shutdown of the groundwater extraction/injection system facilitated a more precise and accurate delineation of the bedrock encasing zone and faults. The incorporation of the Horizontal Flow Barrier (HFB) Package in the current model provided a greater accuracy in both the location and conductance of faults. The HFB Package also allows for much faster computer runs, and a more stable numerical model. Additionally, recovery data allowed for a more precise determination of bedrock storage properties through model calibration.

(2) The flow model was calibrated to three data sets consisting of:

- (a) Water levels measured in June 2004;
- (b) A long-term average data set; and
- (c) Transient data from recovery following shutdown

(3) A good match was attained between measured and simulated values. A Mean Absolute Residual (MAR) of 2.41.ft. was attained during calibration to 212 long-term average target locations. The model also matched prior estimates of groundwater inflow into the model domain, and simulates the general regional flow domain.

(4) The TCE plume produced by the model is a reasonable match to the observed plume, both under current conditions and during development of the plume. The modeled results compare favorably with observed results and the prior model (HEC/Geotrans, 2005).

(5) Modeling Conclusions

(a) Groundwater flow across the site can be conceptualized as consisting of relatively flat gradients located in broad areas between fault zones, where dramatic drops in water levels occur over a very short distance. These fault zones are the controlling hydrologic structures in the model area. The more precise delineation of the bedrock encasing zone, from water level data and use of the HFB package, facilitated a significantly more accurate representation of the flow system.

(b) Calibration to the recovery data were used to analyze the relative influence of parameters on transient water levels. Changes in horizontal hydraulic conductivity primarily affected the total simulated head change over a time interval. Changes in vertical hydraulic conductivity and specific storage primarily affected the initial rebound following shutdown. Changes in specific yield/porosity primarily affected the slope of the recovery curve.

(c) The steady-state and transient calibrations demonstrated the model's ability to replicate changes in water levels resulting from changes in stress on the system. The good match with several independent data sets provides additional validation and reduces the uncertainty of the model. Porosity is important for simulating plume migration. In the past porosity was estimated from tables and calibration of the solute transport model. Calibration to measured recovery provided a physical basis for specific yield and hence porosity values in the bedrock.

(d) The solute transport model was run three years into the future to provide prediction of plume migration. Two methods of representing the current plume configuration (plume initialization) were used. The first method was simply to continue the model using the model calculated present day plume configuration. The second method was to reinitialize the plume based on contouring concentrations measured in monitoring wells in 2005. For both of these configurations the model was run with the source concentrations continued into the future and with the sources removed. The results of these simulations indicate that plume migration will be limited to 300 to 500 ft during the three year period. The results also show that the source area input does not affect the distal portion of the plume; only the area near the sources are affected.

(e) The expanded solute transport sensitivity analysis performed on individual source terms was useful for model calibration and for future plume management decisions. It appears that the Old Industrial Waste Lagoon and Spreading Area were the primary contributors to the main plume extent downgradient of the bedrock block. In addition, the Building 679 source appears to be the primary contributor to the Northeast Boundary Plume.

J. 2007 Groundwater Flow and Transport Model (HEC/Geotrans, 2007)

(1) Calibration of the groundwater flow and solute transport model over the past two years focused on matching groundwater level recovery following the summer 2004 shutdown of the groundwater extraction system. These efforts facilitate a more precise and accurate delineation of the bedrock encasing zone and faults. The incorporation of the Horizontal Flow Barrier Package in the 2006 model provided a greater accuracy in both the location and conductance of faults.

(2) The current flow model was calibrated to long-term water level data starting in 1942. Previous flow models used an assumption of steady-state water levels from 1942 to 1994. This assumption prevented accounting for changes in hydraulic gradients and flow trajectories caused by differential changes in water levels during the period when much of the plume migration took place. Modeling of water level changes during this period assigns the correct driving force to the plume; prior models may have used porosity of distribution coefficient as a calibration factor to adjust plume velocity to obtain a reasonable match to observed concentration data.

(3) The TCE plume produced by the model is a reasonable match to the observed plume, both under current conditions and during the development of the plume. The modeled results compare favorably with observed results and the prior year models.

(4) The accurate simulation of transient groundwater flow conditions from the beginning of plume formation in 1942 to the present provides more realistic simulation of the transient forces that drive plume formation. The transient groundwater flow model simulated the changes in heads and flows during long-term wet and dry periods. Additionally, the model simulated monthly extraction/injection wells for the full length of operation of the pump-and-treat system (1994-2004). The calibrated flow model produced a good match to selected, representative well hydrographs.

(5) As a result of the change to transient flow modeling, the simulated TCE plume initially moved further downgradient than measured. This required a change in effective porosity and sorption coefficient to bring the model back into reasonable calibration. Also, the calibration target of TCE influent concentration (flow weighted average of extraction well concentrations) proved very sensitive to the simulated mass flux applied at the ditches and lagoons. This sensitivity results because the wells located in the bedrock block extract much of the TCE mass and the ditches were a key contributor to contamination within the bedrock block. Identification of calibration targets that are sensitive to model input is important for defining reasonable ranges for the upcoming uncertainty analysis.

(6) The solute transport model was run through 2009 to provide prediction of plume migration in the near future. Two methods of representing the current plume configuration (plume initialization) were used. The first method was simply to continue the model using the model-calculated December 2006 plume configuration. The second method was to reinitialize the plume based on contouring concentrations measured in monitoring wells in October 2006. For both of these configurations the model was run with the source concentrations continued into

the future and with the sources removed. The results of these simulations indicate that plume migration will be limited to approximately 500 ft or less over a three year period. The results also show that the source area input does not affect the distal part of the plume; only the areas near the sources are affected. After completion of a planned model uncertainty analysis, longer-term predictive simulations will be conducted.

4. Future Modeling Efforts

An abstract of each year's modeling activities shall be included in this permit attachment, not later than June 1 of each year (as specified in Table V-3 of Module V.F.1), in order to provide an overall summary of the modeling program. Specific details on modeling activities can be found in the referenced reports.

(HEC, 1999) U.S. Army Corps of Engineers, Hydrologic Engineering Center, 1998
Hydrogeologic Flow Model and Accompanying Solute Transport Model for Tooele Army Depot, Utah, January 1999

(HEC, 2000) U.S. Army Corps of Engineers, Hydrologic Engineering Center, 1999
Hydrogeologic Flow Model and Accompanying Solute Transport Model for Tooele Army Depot, Utah, January 2000

(HEC, 2000a) U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2000
Groundwater Flow Model Recalibration Study

(HEC, 2001/2002) U.S. Army Corps of Engineers, Hydrologic Engineering Center, Tooele Army Depot Groundwater Flow Model, 2001/2002 Recalibration Study, April 2002

(HEC, 2003) U.S. Army Corps of Engineers, Hydrologic Engineering Center, Tooele Army Depot Groundwater Flow and Contaminant Transport Model – 2003, April 2003

(HEC/Geotrans, 2004) Tooele Army Depot Groundwater Flow and Contaminant Transport Model (2004), April 2004

(HEC/Geotrans, 2004a) Addendum to the Tooele Army Depot Flow and Contaminant Transport Model (2004) TCE Transport Sensitivity Analysis – May 26, 2004

(HEC/Geotrans, 2005) Tooele Army Depot Groundwater Flow and Contaminant Transport Model, July 2005

(HEC/Geotrans, 2006) Tooele Army Depot Groundwater Flow and Contaminant Transport Model, July 2006

(HEC/Geotrans, 2007) Tooele Army Depot Groundwater Flow and Contaminant Transport Model, July 2007